AFRL-RW-EG-TR-2008-7088

Design of 50MM Powder to Air or Light Gas Gun Converter

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GRANT NO. FA8651-08-1-0002

JUNE 2008

Final Report for Period September 2007 – May 2008

DISTRIBUTION A: Approved for public release; distribution unlimited.
Approval and Clearance 96 ABW/PA # 08-06-08-359, dated
6 August 2009

AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE

■ Air Force Materiel Command■ United States Air Force Eglin Air Force Base

NOTICE AND SIGNATURE PAGE

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(30-05-2008)*
01-06-2008

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
(September 2007-May 2008

4. TITLE AND SUBTITLE
DESIGN OF 50MM POWDER TO AIR OR LIGHT GAS GUN CONVERTER

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA8651-08-1-0002

5c. PROGRAM ELEMENT NUMBER
62602F

6. AUTHOR(S)
JUSTIN CHIASSON, MATTHEW HOHENSHUTZ, JASON PICONE AND

5d. PROJECT NUMBER
2502

5e. TASK NUMBER
92

5f. WORK UNIT NUMBER
03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DEPARTMENT OF MECHANICAL ENGINEERING
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LOUISIANA

8. PERFORMING ORGANIZATION REPORT NUMBER
NA

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Munitions Directorate
AFRL/RWMW
101 W. Eglin Blvd.Ste 135
Eglin AFB, FL 32542-6810

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL-RW-EG

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RW-EG-TR-2008-7088

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A: Approved for public release; distribution unlimited. Approval and Clearance 96 ABW/PA # 08-06-08-359, dated 6 August 2009.

13. SUPPLEMENTARY NOTES
AVAILABILITY OF THIS REPORT IS SHOWN ON THE NOTICE PAGE. DISTRIBUTION STATEMENT INDICATING AUTHORIZED ACCESS IS ON THE COVER PAGE AND BLOCK 12 OF THIS FORM.

14. ABSTRACT

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This document explains the objectives and progress of the air gun project. The main objective is to design an air or light gas gun to launch a 1 kg projectile up to 2000 ft/s. An update on the overall design of the gun is discussed along with the testing already accomplished and manufacturing plans. The design chosen utilizes a quick release design to hold the sabot in place while allowing the pressure to be built behind it. The sabot can then be quickly released, thus firing the gun. Current budgets along with a Gantt chart are also included in this paper.

15. SUBJECT TERMS
Air gun, gas gun, quick release valve launcher

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					KIRK E. HERZOG
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	38	(850) 882-8979

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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EXECUTIVE SUMMARY

DESIGN OF A 50MM POWDER TO AIR OR LIGHT GAS GUN CONVERTER

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ABSTRACT

This document explains the objectives and progress of the air gun project. The main objective is to design an air or light gas gun to launch a 1 kg projectile up to 2000 ft/s. An update on the overall design of the gun is discussed along with the testing already accomplished and manufacturing plans. The design chosen utilizes a quick release design to hold the sabot in place while allowing the pressure to be built behind it. The sabot can then be quickly released, thus firing the gun. Current budgets along with a Gantt chart are also included in this paper.

INTRODUCTION

The Damage Mechanisms Branch (RWMW) of the Air Force Research Laboratory conducts research on projectile penetration of hardened targets (concrete and soil) on a routine basis to characterize the high strain rate material properties and performance of high-speed penetrators. Experiments are often performed using penetrators that range in size from 0.5 to 4 inches in diameter and that have velocities from 1000 to 5000 feet per second (fps). Currently, the RWMW uses 20mm and 50mm high velocity cannons capable of launching payloads, 50-150 grams in the 20mm and 50-1000 grams in the 50mm, from 700 fps to 4000 fps with +/- 25 fps precision to perform these experiments.

Existing 20mm and 50mm powder guns have reasonable ability to meet the package launch requirements but require munitions handlers and EOD troops to conduct the experiments due to the use of energetic materials (i.e., propellant). Elimination of the propellant charge will eliminate the need for extra personnel to supervise the energetic material handling, will reduce the safety hazards, and will provide tighter control of the launch conditions improving experimental accuracy.

Light gas guns are in use throughout the world to fire projectiles of various sizes at high velocities in order to test the projectile or the target or both. Many of these guns have been designed, built, and tested throughout the last fifty to sixty years with some novel firing mechanism designs, but for the most part the guns use the same overall design ideas to accomplish the firing.

LITERATURE REVIEW

One of the important tasks of this project was researching and gaining experience with interior ballistics and light gas guns before designing the new breech. Research was started by performing a search for journal articles on light gas guns on the internet. Several articles were found which provided a good background to begin the project. After an exhaustive search of the internet, the library was searched for books on pressure vessel design and master's thesis on light gas guns. Several books were found on pressure vessel design which provided the basis for the necessary calculations. Master's theses were found that presented ideas for the fast acting valve and improvements to the mathematical model of the gun.

FINAL DESIGN

The primary objectives of this project were to design interchangeable hardware to temporarily convert the existing 50mm barrel, as currently mounted, into air or light gas guns, fabricate the necessary hardware, and install the hardware at Eglin Air Force Base along with executing a test series to develop the pressure curves and/or equations to determine the necessary control settings to achieve a maximum predetermined velocity of 2,000 fps for a known payload mass with error less than +/- 25 fps.

The constraints on the design of this system were such that any existing ideas and designs known to the group through journal and internet research and thesis papers were of no practical use to reach the design requirements. The common forms of firing test projectiles are to use explosives, burst disks, or light gases or some combination of the three to reach high speeds, but neither explosives nor rupture disks were allowed in the design; this coupled with the budgetary constraints forced a new design to be conceived.

PROJECTILE

Instead of the standard design that uses either a quick release valve or a series of rupture disks to simulate the instantaneousness of an explosion, this design uses the projectile itself to "plug" the breech and hold the pressure in until the desired moment. The seal between the vessel and the barrel is provided by both the flair of the obturator on the back end of the projectile and the tight fit of the obturator to the breech with some type of petroleum based lubricant surrounding it and filling in the microscopic holes. The projectile is held in place by a series of ball bearings that seat in the breech walls and partially extend, at most one quarter of an inch, into the groove cut into the projectile. The bearings press against a steel washer that is fitted between the obturator and the front end of the projectile. Also a metal washer and a plastic piece will be inserted. The washer is needed to hold back the 20,000 lb force pushing on the projectile. The original sabot used by Eglin AFB which houses the penetrator is used, but the obturator is modified by using Nylon instead of Polypropylux as the material.

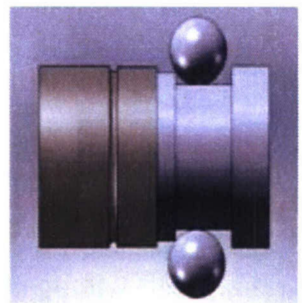

Figure 1: Obturator, steel washer, and bearings.

BREECH AND COUPLES

The breech system works similar to a quick release connection mechanism used on high pressure hoses. Four ball bearings that seat in the breech and hold the projectile in place are themselves held in place by a movable sleeve that encircles the breech. When the sleeve is moved to a particular position the ball bearings are forced to move up and out of the way of the projectile, which is itself forced forward by the back pressure of the pressure vessel. Instead of sliding in a lateral direction, forward and reverse, as in a typical quick release mechanism, the sleeve rotates about the breech.

The large pressure behind the projectile places a large force on the ball bearing which is transmitted to the sleeve producing a large static friction force that needs to be overcome, in the realm of 3,000 lbf, for the sleeve to move. This large force is most easily overcome by using the principles of rotation and torque arms and putting them to practice by creating the sleeve to rotate about the breech and bearings and using a torque arm to more easily generate the required forces. As the sleeve rotates the balls are allowed to move up and down by following the contour of the inner geometry of the sleeve.

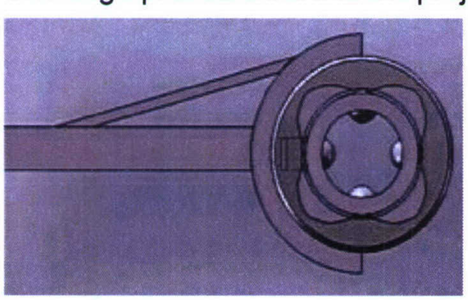

Figure 2: Cross section of the torque arm, sleeve, bearings, and breech.

A winch is mounted onto angle iron, which is welded to the I-beam directly beneath the breech. A u-bolt is attached to the eye of the winch cable which is then placed on the torque arm. This allows for the easy placement and removal of the cable onto the arm because once the winch is activated the arm is pulled down to turn ninety degrees wherewith the hook then detaches from the arm to prevent the winch from exerting a higher force on the system than is designed. The projectile will be released when the arm turns forty five degrees.

Couples are used to connect both the vessel to the breech and the breech to the barrel. A couple is threaded onto the barrel at which point the breech is then threaded into the couple. The threads are standard, right hand threading on both sides of the couple.
The projectile is loaded into the system from the pressure vessel end of the breech which in turn calls for a relatively easy connection between the pressure vessel and breech for easy access. This ease of access is provided by a reverse threaded couple. The nozzle on the pressure vessel is reverse threaded whereas the breech is normally threaded which allows for the couple to be threaded and tightened to both the breech and pressure vessel at the same time making the connection and disconnection simplistic for the constant need of placing a projectile into the breech. The couple is tightened until the face of the pressure vessel nozzle contacts the face of the breech. Pipe dope is used on all threaded connections to help prevent gas leakage to the atmosphere.

A solenoid valve is used to lock the sleeve in place while the vessel is being pressurized. When the gun is ready to be fired the solenoid is opened and the winch activated to turn the sleeve. There is also a manual safety pin that is removed directly before the area is cleared for pressurization of the system.

PRESSURE VESSEL

The pressure vessel was constructed by the Air Force at the Eglin base by converting a used 2,000 lb penetrator bomb casing into a pressure holding device. The plate that the nozzle is welded to is held in place at the front of the vessel by a threaded ring and is also the section of the vessel that the inlet and outlet connections are placed as well as the pressure gauges. Helium or air is pumped into the pressure vessel until the desired pressure is reached. A Haskel pump is used to compress the light gas.

SUPPORT STRUCTURE

The frame for the cart is made from welded together 2x2 square steel tubing. The front of the cart is made to straddle the I-beam to allow the nozzle of the pressure vessel to come far enough forward to correctly attach to the breech. Boat jack wheels are placed on the four corners of the frame and in the middle of the frame on both sides which allow the cart to be independently leveled in order to align the vessel with the breech, and also provide mobility for the cart to traverse obstacles by lowering and raising wheels as needed.

The vessel is supported by and placed in a horizontally free floating car that sits atop the frame but is independent of it. The car has four single flanged wheels attached to it that roll on and are guided by the frame. This pressure vessel support structure design gives the ability to not only move the vessel but also traverse small obstacles while providing the ability to level the vessel with the breech and barrel and account for the movement produced by recoil while keeping the vessel in line and level.

The breech is also supported by a cart. The cart has bearings for wheels which allow the cart to roll easily during recoil. A large job of the cart is to support the breech while the 3,000 lbf force is exerted on the torque arm to turn the sleeve. This ensures that the barrel will not be tilted when the sleeve is turned.

FABRICATION AND TESTING

Before fabrication could be started, a simple test rig was assembled to confirm the feasibility of the design. The breach was made of carbon steel pipe and the projectile was made from nylon and polypropylene. Also different geometries for the metal insert were created to find the most efficient shape. The concrete compression system in the Civil Engineering lab was used for the test rig.

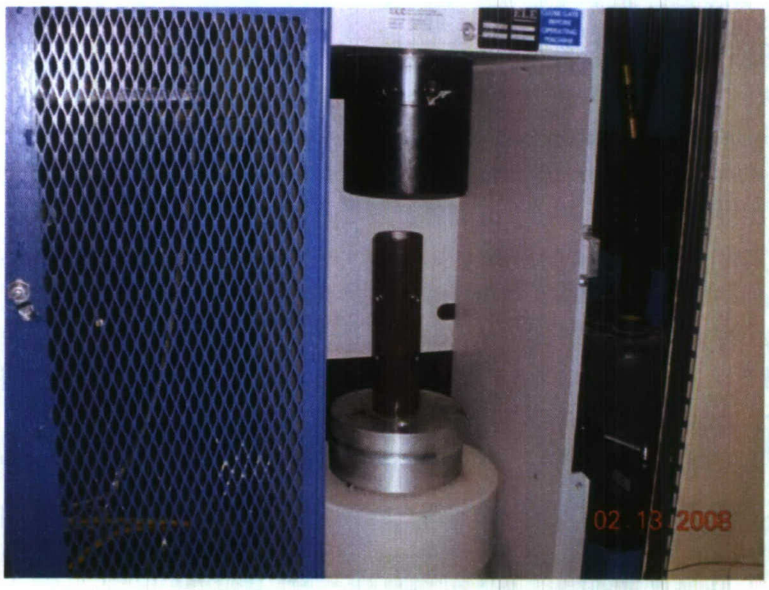

Figure 3: Test rig in compressive machine

The first test done was just using the plastic to hold back the pressure. This test failed, because the plastic deformed to the point that it would not come out of the breech without excessive force. The next test was done using a solid metal plate. The metal plate slightly deformed but was strong enough to hold back the pressure. The final test was the metal plate with a hole in the center. This geometry also was successful. Based on these results the washer design was chosen because it is strong enough to hold the pressure and it also minimizes the weight added to the projectile.

Once the design was confirmed, the parts were ordered and fabrication started. The two large couples and the breech had to be outsourced to a machine shop because the LSU shop did not have the capabilities to produce them. The two couples were too large for any of the lathes to hold. The breech needed to be precise which could not be done here. The rest of the pieces were fabricated in the shop by the team. The frame for the pressure vessel was cut using a band saw and then welded together. The vessel and breech supports were cut on the water jet in the Chemical Engineering shop. The three pieces for the projectile and the sleeve were produced on the CNC mill. Also the sleeve went through a heat treatment in order to increase the hardness. The sleeve was heated to 900 °C for two hours and then quenched in oil to create martensite. It was then reheated to 420 °C for forty five minutes to create tempered martensite.

PROTOYPE RESULTS AND ANALYSIS

After fabrication was completed, the team traveled to Florida to assemble and test fire the gun. A few problems arose during the assembly of the gun. First, due to miscommunication the length of the threads for the larger couple was too long. The couple was taken to the machine shop at the base and cut down to proper size. Next, the sleeve did not fit tightly on the barrel. A spacer needed to be inserted in order to simplify the loading process and to stop unwanted vibrations after firing. Another problem was that the pressure vessel did not seal properly. This was fixed by bypassing the pump to shorten the filling time and shooting at lower pressures. The air supply tank was connected straight to the pressure vessel, and the valve was opened completely. When the desired pressure was reached the gun was fired.

After the assembly was completed, four shots were taken. The first two were successful. The first shot was at 338 psi of air with a payload of 1110.6 grams. The expected velocity for this pressure and mass was around 450 ft/s. The projectile was fired at 360 ft/s. The second shot was at 910 psi of air with a payload of 762 grams and an expected velocity of 940 ft/s. This projectile was fired at 1008 ft/s. Due to time constraints the test plan was altered for the next shot. This shot was taken at 231 psi of air with a mass of 761 g. This shot was taken at low the same pressure/mass ratio to determine if the gun fires consistently. The velocity should have been the same as the first shot but this attempt failed. The projectile came out of the barrel but the obturator became wedged a third of the way down the barrel. The fourth shot, which used helium, also was unsuccessful. It was taken at 1189 psi and a payload of 763.2 grams. Again the projectile came out of the barrel but the obturator was wedged in the middle of the barrel. The failure of these two shots was due to a few reasons. First, the sleeve slightly shifted back after the second shot and the team did not notice. The balls did not completely release, which caused the obturator to release slowly and possible blow by to occur. Also, once the projectile is released gas is allowed to escape through the four holes in the breech. For the low pressure shot, any volume lost is critical and needed force is lost. For the helium shot, the helium leaked extremely quickly through the holes to lose pressure. The helium also may have leaked past the projectile, because the pressure vessel was leaking and it was not known if the projectile sealed properly. The final problem deals with the plastic filler that was inserted into the pressure vessel. When the gun is fired a pressure differential is created and the plastic filler is pushed to the front of the pressure vessel. The filler could have possibly moved all the way forward and restricted the gas from coming out of the pressure vessel.

IMPROVEMENTS

Improvements can be made in order to produce more successful shots. First, the sleeve needs to be sealed to prevent gas from leaking out of the breech after the projectile is released. This will be done by inserting a metal spacer, which will also help to steady the sleeve, on one side of the sleeve. On the other side of the sleeve an o-ring will inserted to prevent leaks. Next, a stop will be welded to the breech to ensure that the sleeve is positioned correctly. Also, the pieces of the sabot will be decreased in diameter by ten thousandths, because the two shots that went through the barrel were slightly extruded. Finally the plastic filler needs to be secured to the back of vessel or moved back after each shot. With these improvements, the gun should be able fire better and more consistent. Another improvement that allows for a quicker turn around time is to add handles to the breech/vessel couple. This will allow the couple to be quickly and easily tightened to the breech and vessel.

CONCLUSIONS

The quick release design was a great improvement from the other designs. This design allows for an instantaneous release of the projectile and the driving gas. The gas is allowed to flow through the barrel without being choked through a small valve. The overall set up took some time but the turn around time between shots was as expected. Although the design objectives were not met due to time constraints, the concepts of the design were shown to be feasible by the experimentation. The two successful shots followed the empirical data and show that the design has a good chance of being effective with the suggested improvements.

Project Summary

The Damage Mechanisms Branch (RWMW) of the Air Force Research Laboratory conducts research on projectile penetration of hardened targets (concrete and soil) on a routine basis to characterize the high strain rate material properties and performance of high-speed penetrators. Experiments are often performed using penetrators that range in size from 0.5 to 4 inches in diameter and that have velocities from 1000 to 5000 feet per second (fps). Currently, the RWMW uses 20mm and 50mm high velocity cannons capable of launching payloads, 50-150 grams in the 20mm and 50-1000 grams in the 50mm, from 700 fps to 4000 fps with +/- 25 fps precision to perform these experiments.

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Light gas guns are in use throughout the world to fire projectiles of various sizes at high velocities in order to test the projectile or the target or both. Many of these guns have been designed, built, and tested throughout the last fifty to sixty years with some novel firing mechanism designs. However, these guns use the same basic design ideas to accomplish the firing. The common design is one that starts the firing process by means of explosive propellants. These propellants are used to drive a piston into a cylinder of light gas. The piston compresses the gas, consequently raising the temperature and pressure. Separating the light gas and projectile is a burst disk set to some specific burst pressure. Once the pressure reaches the set value, the burst disk will break to let the gas propel the projectile. Most guns with the same high speed and low weight projectile requirements use this design in one form or another some guns replacing the powder charge with compressed gas, and some guns using valves instead of bursting devices.

Background

One of the important tasks of this project was researching and gaining experience with interior ballistics and light gas guns before designing the new breech. Research was started by performing a search for journal articles on light gas guns on the internet. Several articles were found which provided a good background to begin the project. After an exhaustive search of the internet, the library was searched for books on pressure vessel design and master's thesis on light gas guns. Several books were found on pressure vessel design which provided the basis for the necessary calculations. Master's theses were found that presented ideas for the fast acting valve and improvements to the mathematical model of the gun.

The system must be capable of delivering a maximum load of a 1 kg projectile at a velocity of 2000 ft s^{-1}. In order to accomplish this goal, the first question that needed to be answered was what are the necessary pressures and temperatures of particular gases that should be used to reach this requirement. A mathematical model of the gun was built in the early stages of design that gave an approximate range of pressures for projectile velocities. Many articles gave experimental results from their guns, but the scale of the guns and projectiles were much smaller than the scale of this project; therefore, the ability to compare these results to this project was questionable. However, two articles in particular have been used to refine the mathematical model developed for this gun. The first of these articles was "A 50 mm bore gas gun for dynamic loading of materials and structures" (Bourne, 2003). The experimental data from this project helped verify the model built for this system. The data from this paper was acceptable for a comparison to this project because the gun in the paper is dimensionally similar to the gun at Eglin. Both guns are 50 mm with barrel lengths of fifteen feet in the paper and twenty feet at Eglin. Also, the breech is arranged such that temperature rises in the driver gas are negligible, which mirrors the setup of this project. The projectile velocity versus pressure test curves from Bourne can be seen in 43.

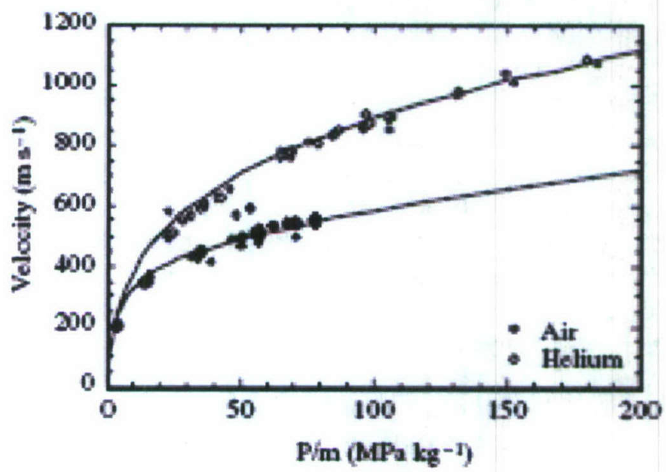

Figure 4: Performance curves (pressure/mass of projectile versus velocity achieved) for projectiles fired with air and helium. The lower is for air and the upper is for helium (Bourne, 2003).

A theoretical comparison between differing gases and projectile performance was also made by Bourne and can be seen in Figure 5.

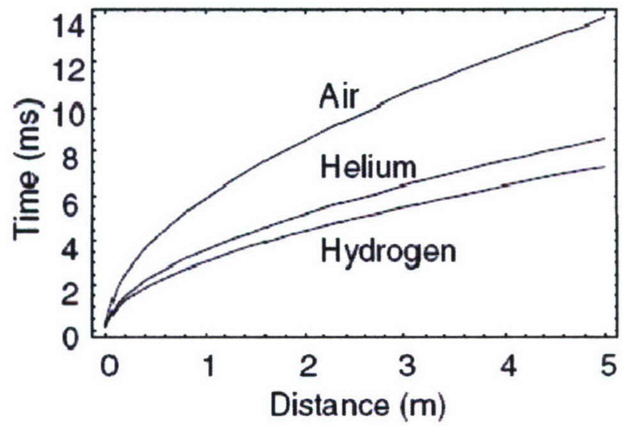

Figure 5: Projectile travel history down barrel using the propellant gases air, helium, and hydrogen (Bourne, 2003).

First, referring to Figure 4, it is shown that the velocity of the projectile is significantly higher when helium is used as the driver gas versus air. An even more important aspect of these curves is the opportunity to understand realistically what energy it would take to make a 1 kg projectile travel at 4000 ft s^{-1}, or roughly 1200 m s^{-1}, which is the upper bound of the graph. To achieve these goals a helium pressure of greater than 200 MPa, or 29,000 psi, would be necessary, and a driver gas of air at the same pressures would only achieve a speed of roughly 700 m s^{-1}, or 2300 ft s^{-1}, well below the goals set forth in this project. Similar to Figure 4, Figure 5 shows the velocity performance of the projectile is highly dependent on the driver gas. Figure 6 shows the comparison between time and the distance the projectile travels down the barrel of the gun. The figure shows the lighter the driver gas, the faster the projectile travels down the barrel which translates to a faster exit velocity. This result was expected because of the higher sound speeds of helium and hydrogen in comparison to air.

Another journal article that has played an important role in understanding the dynamics of the driving gas and improving the mathematical model created in the beginning of the design process is, "A simple small-bore laboratory gas-gun" (Hutchings & Winter, 1975). The gun used by Hutchings and Winter for experimentation is on a smaller scale than the gun in this project, with dimensions of a 16 mm bore and a 1 m long barrel; therefore, the exact experimental results are not very useful in predicting the performance of the current project's system. However, a few notes have been taken from this paper that supports the assumptions made for the theoretical prediction of the system. Figure 6 clearly illustrates the inadequacies of mathematically modeling the internal ballistics of an air or light gas gun.

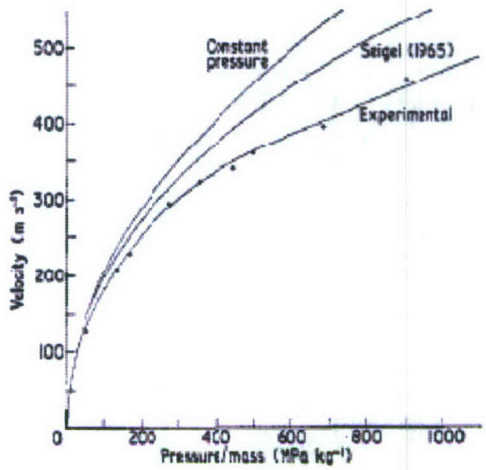

Figure 6: Performance curve with helium, compared with the prediction of the two theories (Hutchings & Winter, 1975).

The lowest curve of Figure 6 was of experimental results while the two upper curves were produced by different modeling techniques. The uppermost curve was produced using constant pressure assumptions by assuming an infinite volume reservoir. This method ignores the properties of the gases such as viscosity and density while also ignoring the effects of propagating pressure waves in the system (Hutchings & Winter, 1975). The middle curve produces a better approximation of the workings of internal gas dynamics by taking into account the adiabatic assumptions of the gas expansion as well as the pressure fronts that propagate while also recognizing the finite gas reservoir (Hutchings & Winter, 1975). It can then be seen that mathematical models are useful in predicting trends, but they should not be the only form of information used in design. If possible, mathematical models used should consider as many realistic assumptions as possible. Further research was conducted which resulted in the discovery of LSU thesis papers, one of which helped refine the theoretical model from something resembling that of the uppermost curve of Figure 6 to a better approximation that would most likely fall between the uppermost and middle curves.

The thesis, "A Mathematical Model of a Two-Stage Light Gas Gun with a Deformable Piston" (Patin, 1985) was used to enhance the simplified theoretical model by incorporating the shock propagation in front of the projectile as it travels down the barrel, and instead of assuming an infinite reservoir of driver gas, an isentropic stagnation pressure relation that changes depending on velocity of projectile was used. Also, the friction associated with the barrel and piston was incorporated. The theoretical relationship between the pressure of helium, the speed of the projectile, and the mass of the projectile as derived from the updated model is seen in Figure 7.

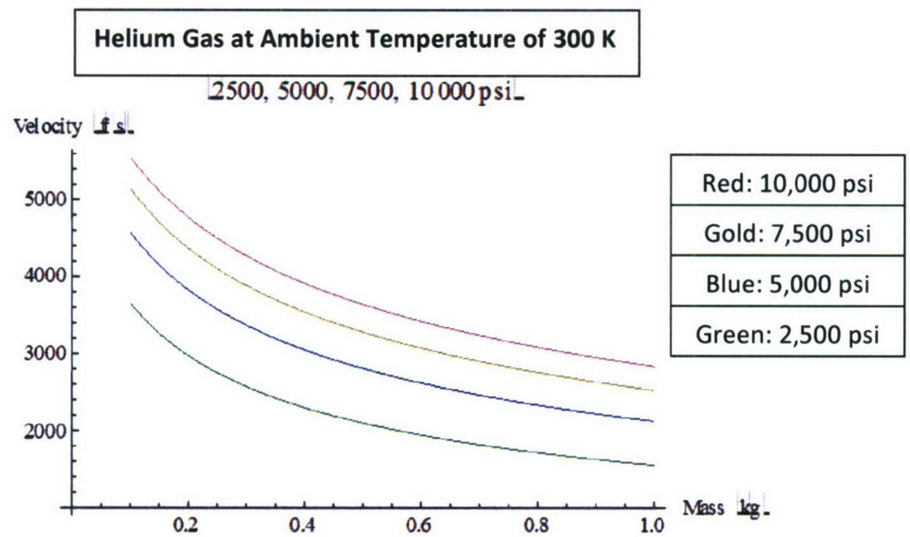

Figure 7: Theoretical model of velocity versus mass of the projectile and pressure of the helium driver gas at ambient temperature.

With the understanding that more than a mathematical model was needed for designing this project, both Bourne's experimental curves from Figure 4 and the updated mathematical model that was produced for the current system, Figure 7, were referenced, and they showed that the pressures needed for the maximum requirements of the project to be met would require helium in a range between 20,000 and 35,000 psi and that using air was unrealistic. After extensive brainstorming and research, the group did not feel that these pressures were attainable with the budget presented. With this knowledge the sponsor lowered the requirements of the project to a maximum velocity of 2000 ft s^{-1} at the same maximum payload of 1 kg with an emphasis on being able to control the projectile velocity accurately. Again, looking back to Bourne's curves and the current mathematical model showed that somewhere between 5000 and 6000 psi of helium was needed to achieve the updated requirements. This could be achieved by a relatively inexpensive helium booster pump. Hence, the working gas that has been chosen for this project is helium with the knowledge that air could also be used, but with substantial losses in performance.

Many designs were presented in the journal articles and thesis papers, but many of the designs used equipment such as burst disks, fast acting valves, and explosives or compressors to obtain high pressures in the driver gas. Since neither explosives nor burst disks are permissible in this project, it would be expected to use high pressure compressors and fast acting valves to launch the projectile, but the current system is much larger than any of the guns in the researched papers. The larger scale of this gun would require valves and compressors on a much larger scale which would drive the project cost much higher than the $5000 budget. Even with the reduced velocity requirements, a high pressure compressor is still needed to provide the driver gas.

Because this compressor would take up most of the budget, the sponsor decided to purchase the compressor with funds external to the project. With the compressor taken care of, designing a pressure vessel to hold the working gas and a fast acting valve system to closely replicate explosions and burst disks became the focus of this project. The solutions to these problems can be found in the following sections.

Prototype Design and Fabrication

Basic calculations were needed to obtain an idea of the values needed to design the gun, mainly pressure and valve opening time, at a design condition of 6,000 psi in the pressure vessel acting directly on the obturator. A simplified approach was taken to solving for these values. Two main assumptions were made for these calculations: isotropic expansion and the working fluid was an ideal gas. Isotropic expansion means that the expansion has to be adiabatic, which results in no friction. Constants frequently used in calculations were the following: V_0 was initial volume, m_b was the mass of projectile, was the final velocity, L was the length of barrel, A was the cross-sectional area of barrel, γ was C_p/C_v for the driver gas, P_0 was the initial pressure, a_a was the speed of sound in air, and γ_a was the ratio of specific heat of air.

The first model was a simple summation of the forces on the projectile. The forces on the projectile were shown in Figure 8.

Figure 8: Summation of Forces on Projectile

The first force examined was the base pressure. A relationship between pressure and volume was found resulting from the isotropic assumption:

$$PV^{\gamma} = Constant$$

Equation 1

Based upon this relationship the average pressure in the tank was expressed as:

$$P = P_0(\frac{V_0}{V_0 + Ax})^{\gamma}$$

Equation 2

However, by assuming the gas isotropically expanded, there were no expansion waves shooting from the back of the projectile to equalize the pressure. But, the mathematics associated with the expansion waves were above undergraduate level math. In order to accommodate for this, an isotropic stagnation pressure relation was used to relate the average pressure in the tank to the pressure at the base of the projectile.

$$P_b = P(1 + \frac{\dot{x}^2}{2\gamma^2 RT})^{\frac{-\gamma}{\gamma-1}}$$

Equation 3

The next force to analyze was from atmospheric pressure. As the projectile travels down the barrel, a shock wave forms almost instantaneously in front of it. By assuming the air between the wave and the projectile equalizes quickly, one can use the basic shock wave equation to find the pressure in front of the projectile.

$$P_f = P_{Atm}(1 + (\frac{\dot{x}}{a_a})^2 \frac{\gamma_a(\gamma_a + 1)}{4} + \frac{\gamma_a \dot{x}}{a_a}\sqrt{(1 + (\frac{\gamma_a + 1}{4})^2 (\frac{\dot{x}}{a_a})^2}$$

Equation 4

The final force left to evaluate was the frictional force. The frictional force was due to the obturator expanding and contacting the surface of the barrel. It was modeled by means of Coulomb friction which is a function of the base pressure and proportional to the Coulomb coefficient of friction, μ.

$$F = \mu \pi m D^2 P_b$$

Equation 5

Once all the forces on the projectile were known, Newton's second law could be used.

$$\frac{d^2x}{dt^2} = (P_bA - P_fA - F)/m$$

Equation 6

$$x(0) = 0$$

Equation 7

$$\dot{x}(0) = 0$$

Equation 8

Since there was no dependence on t, the differential equation could be transformed.

$$\frac{dv}{dx} = (P_bA - P_fA - F)/mv$$

Equation 9

$$v(0) = 0$$

Equation 10

These equations could be integrated using a numerical differential equation solver and the graphs are shown in the appendix. However, certain disadvantages existed in this model due to the assumptions made. The major disadvantage was from the isotropic assumption. As stated above, this eliminated any pressure waves. At projectile speeds near the driver gas' speed of sound, the model was not very accurate because the waves start to play a large role in the dynamics. Also, these calculations assumed that a burst disks is used. No losses from the valve were taken into account.

The design must meet the requirements of the sponsor. The first set of requirements dealt with the performance of the canon. It must be able to launch a payload weighing from 0.1-1.0 kg at a velocity range of 700-2000 ft/s. Also, the velocity of each shot must be predicted within ±25 ft/s. Next, the sponsor wanted continuous variability within the velocity range. The next set of requirements dealt with the set up of the gun. The design needed to be interchangeable with the existing powder breech. In order to be interchangeable, the new breech must be able to be attached and removed from the barrel, and then the explosive breech can be connected. Finally, it needed to have a turnaround time between shots of one hour.

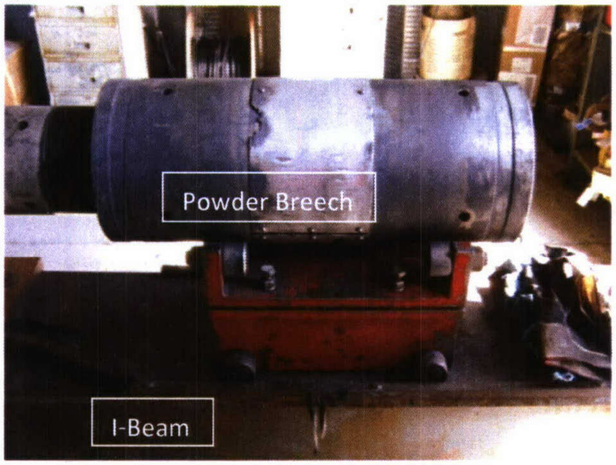

Figure 9: Explosive Breech

There are two main components to the air gun: the fast acting valve and the pressure vessel. In order to meet the performance requirments, each component had its own set of needs. To reach the goal of 2000 ft/s, the pressure vessel needed to hold 6000 psi and hold a volume of at least 20 L. This requirment was based on the mathematical model that was developed by the group. Below 20 L, the final velocity decreases sharply, shown in Figure 10.

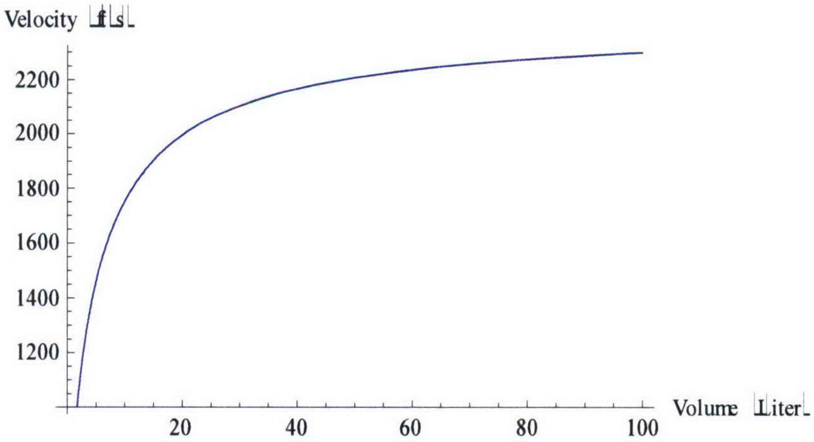

Figure 10: Velocity vs. Pressure Vessel Volume

The fast acting valve had its own design requirements. Most importantly, it had to be able to open in approximately 1 ms. It was determined that the projectile takes 18 ms to reach the end of the barrel. The valve had to open an order of magnitude less than this time so the projectile would feel the full force of the pressure pushing behind it. The next requirement was the valve needed to seal the breech. The leak rate needed for a good seal cannot be determined at this time because it is dependent upon the compressor, which has yet to be procurred by the sponsor. However, the leak rate should be at least two orders of magnitude less than the compressor's inlet flow rate. The final requirement of the valve was that it needed to be opened from a remote location. This is a safety requirement imposed by the sponsor. Safety requirments are discussed in more detail in a later section.

The overall design is seen in Figure below. Helium or air is pumped into the pressure vessel until the desired pressure is reached. A Haskel pump will be used to compress the gas. The seal for the vessel is provided by the obturator on the projectile. To fire the gun a winch will pull down the torque arm, thus rotating the sleeve and releasing the projectile. The breech will be connected to the existing barrel on the I-beam. Each part will be discussed in further detail.

Figure 11: Concept Schematic

Breech

The breech will work similar to a quick release mechanism used on high pressure hoses. Four ball bearings will be held in place by a sleeve. When the sleeve is moved the ball bearings will be allowed move up which will allow the projectile to move.

Figure 12: Ball bearing engaged with obturator

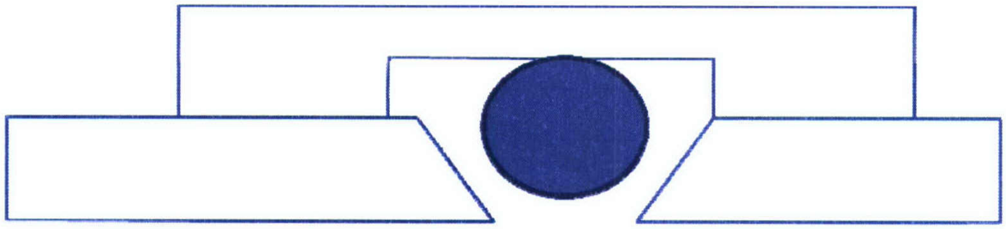

Figure 13: Ball bearing released

Instead of sliding forward, the sleeve for the breech will rotate. The sleeve needs to rotate because a large force is needed to overcome the friction between the bearings and the sleeve. As the sleeve rotates the balls will be allowed to move up following the contour.

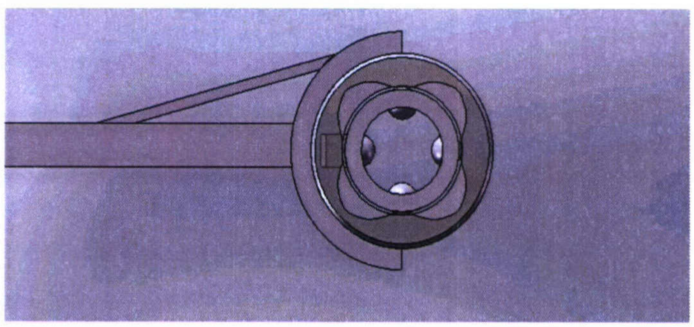

Figure 14: Sleeve cross-section

A torque arm is attached to the sleeve in order to decrease the amount of force need to rotate the sleeve. With the arm a 3000 lb force is needed to rotate the sleeve.

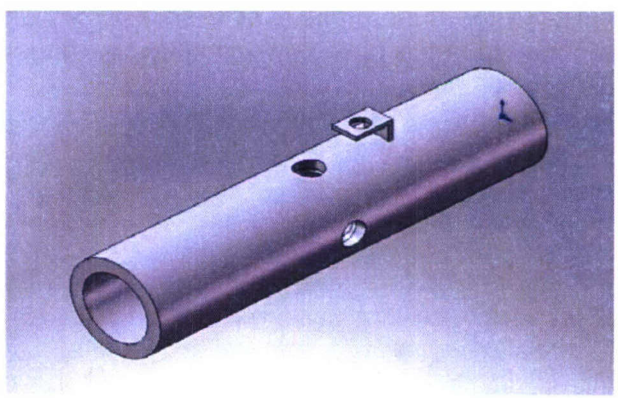

Figure 15: Breech

The breech is shown in Fig 15. The latch on the top will be used to align the sleeve in the closed position. A solenoid valve will be used to lock the sleeve in place while the vessel is being pressurized. When the gun is ready to be fired the solenoid will be opened and the winch activated to turn the sleeve.

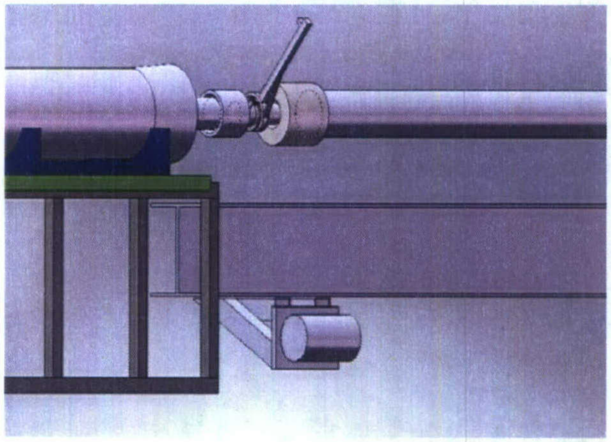

Figure 16: Side view of system

Fig16 shows the location of the winch. The winch will be mounted with angle iron to the I-beam directly beneath the breech. The cable will be attached to the torque with a hook. Once the arm turns ninety degrees, the hook will detach from the arm. The projectile will be released when the arm turns forty five degrees.

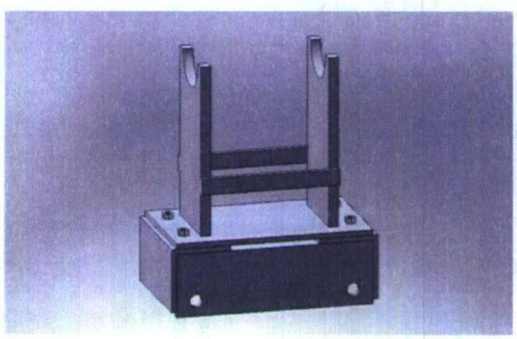

Figure 17: Breech cart

The breech will be supported by a cart. The cart will have bearings for wheels which will allow the cart to roll easily during recoil. The cart also supports the breech while the

3000 lb force is exerted on the torque arm to turn the sleeve. This ensures that the barrel will not be tilted when the sleeve is turned.

Cart

The frame for the cart, seen in Fig 18 will be made from 2x2 square steel tubing. The cart will be made to fit around the I-beam. Boat jack wheels will be placed on all four corners of the frame which will allow the cart to be leveled in order to align the vessel with the breech. The vessel will be place in a cart atop the frame. The cart will have four wheels that will roll on a track similar to a train.

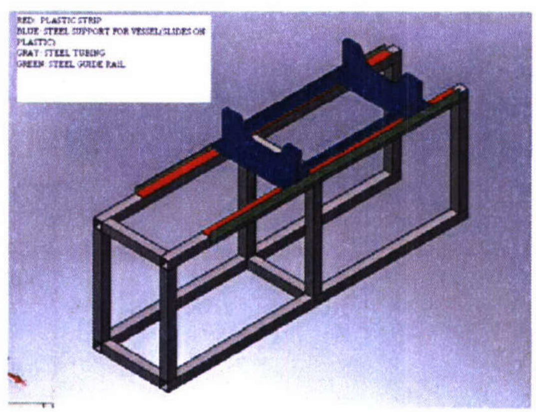

Figure 18: Pressure vessel cart

Couples

A couple will be used to connect the vessel to the breech. The nozzle will be reverse threaded and the breech will be normally threaded which will allow the couple to be tightened onto both at the same time. The couple will be tightened until the nozzle contacts the breech. A copper gasket will be placed in between the nozzle and breech in order to seal the gas in the vessel. A similar couple will also be used to connect the breech to the barrel. The threads will be standard on both sides of the couple. The couple will be threaded onto the barrel, and then the breech will be threaded into the couple.

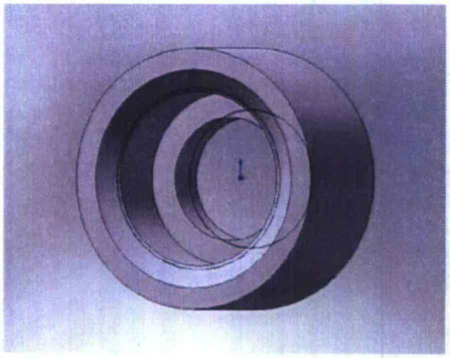

Figure 19: Couple

Sabot

The original sabot will be used, but the obturator will be modified. Also a metal washer and a plastic piece will be inserted. The washer is needed to hold back the 20000 lb force pushing on the projectile. The extra plastic piece is used to connect the obturator to the sabot.

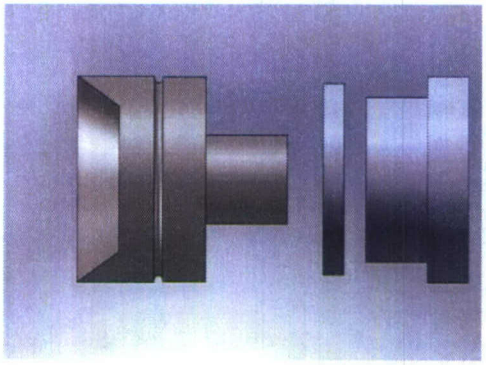

Figure 20: Obturator, steel washer, and plastic piece

Figure 21 shows the three pieces assembled with the ball bearings in place.

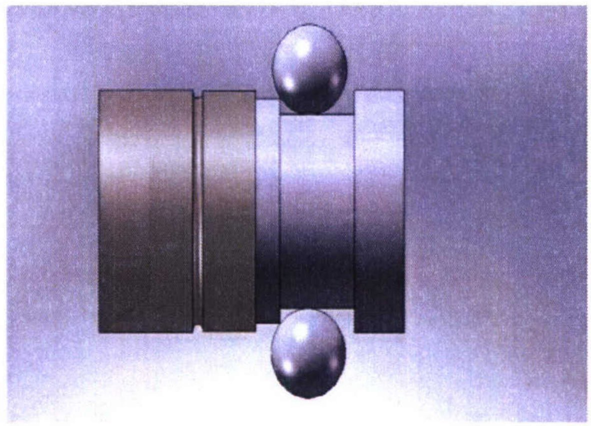

Figure 21: Assembled obturator, steel washer, and plastic piece engaged by ball bearings

As before, the obturator will seal the gas behind the projectile.

Testing

Testing was done to assure the sabot could successfully be held in place with the pressure vessel fully pressurized. First, a test rig was built that would be able to ensure the bearings could hold the sabot at a force of approximately 10,000 pounds. The rig consisted of two 8" x 8" x ¼" steel plates bolted together with six 3' x ¾" steel rods. A six ton jack was then placed on a metal plate with the breech on top. The plates were them clamped down onto the breech, allowing the jack to put a force on the sabot. Figure 22 shows the final setup.

Figure 22 Test Rig

The test showed that the bearings could hold the sabot in place. The test involved using one row of four bearings to hold the sabot. The jack pumped as many times as possible before it could not be pumped anymore which was approximately five tons of force. The bearings indented into the sabot approximately ¼" without deforming the plastic outward to prevent the sabot from traveling smoothly down the breech.

The testing done proved the bearings would hold the sabot, but a more definitive test was needed. The force exerted on the sabot needed to be quantified, so a hydraulic jack in the Civil Engineering Department was used. The jack had a capacity of 300,000 lbf with an accuracy of +/- 100 lbf.

Figure 23: Hydraulic jack configuration

The first test done was one row of four bearings on the plastic at 30,000 lbf. The plastic deformed greatly, the bearings dimpled approximately 1" into the sabot, and the plastic deformed outwardly which prevented it from smoothly moving down the barrel. In order to overcome this problem, metal washers were added to seat the bearings against.

Two washers were tested: one with a ¼" diameter hole, and one with a ¾" diameter hole. Both were individually tested in the jack to 30,000 lbf. Both deformed less than ¼" when the bearings seated in the washer. With both washers adequately holding the force, it was decided to use the ¾" diameter washer because of its smaller weight.

Manufacturing

Once the design was confirmed, the parts were ordered and fabrication started. The two large couples and the breech had to be outsourced to a machine shop because the LSU shop did not have the capabilities to produce them. The two couples were too large for any of the lathes to hold. The breech needed to be precise which could not be done here. The rest of the pieces were fabricated in the shop by the team. The frame for the pressure vessel was cut using a band saw and then welded together. The vessel and breech supports were cut on the water jet in the Chemical Engineering shop. The three pieces for the projectile and the sleeve were produced on the CNC mill. Also the sleeve went through a heat treatment in order to increase the hardness. The sleeve was heated to 900 °C for two hours and then quenched in oil to create martensite. It was then reheated to 420 °C for forty five minutes to create tempered martensite.

Safety

Safety was a major concern while operation the air gun at high pressures. There are already many safety precautions in place for firing the powder gun. The main ones are:

1. All personnel must be inside during firing.
2. All of the buildings are constructed of reinforced concrete.
3. The gun is fired remotely from the control room.

Also, for the air gun some new features were added. A visual pressure gauge is on the pressure vessel to allow the personnel to see that the vessel is empty. An automatic relief valve will not allow the vessel to be pressurized over 6,000psi. A manual relief allows the vessel to be depressurized from the control room in case the gun miss fires. There are also two safety pins used to prevent the gun from firing. One is a manual pin that is removed before the personnel go into the bunker. The other is an automated pin that is removed seconds before the gun is fired. Also, many other precautions are found in the operation instructions, which is a detail manual on how to fire the gun.

Budget

The allowed budget for the project was $5,000. Some other help was received to keep the cost down. The pressure vessel was supplied by the AWEF. Also, the breech and couples were out sourced for free which enabled the project to be completed under budget. The description of the cost can be seen in the table below. The total money spent was approximately $4,850.

Component	Price ($)
Testing	200
Instrumentation	1000
Carts	1400
Breech, Sleeve, and Couples	1250
Winch	300
Projectiles	300
Miscellaneous	400
Total	4850

Figure 24: Budget

Project Schedule

The project followed the schedule for the second semester. The testing dates were set for April 2nd-4th. The breech and couple were received on April 1st, but they were not made correctly. These three pieces were fixed on Wednesday and arrive at the base that afternoon. Other than those problems everything else was completed on time. Further scheduling details can be seen in the Gantt chart.

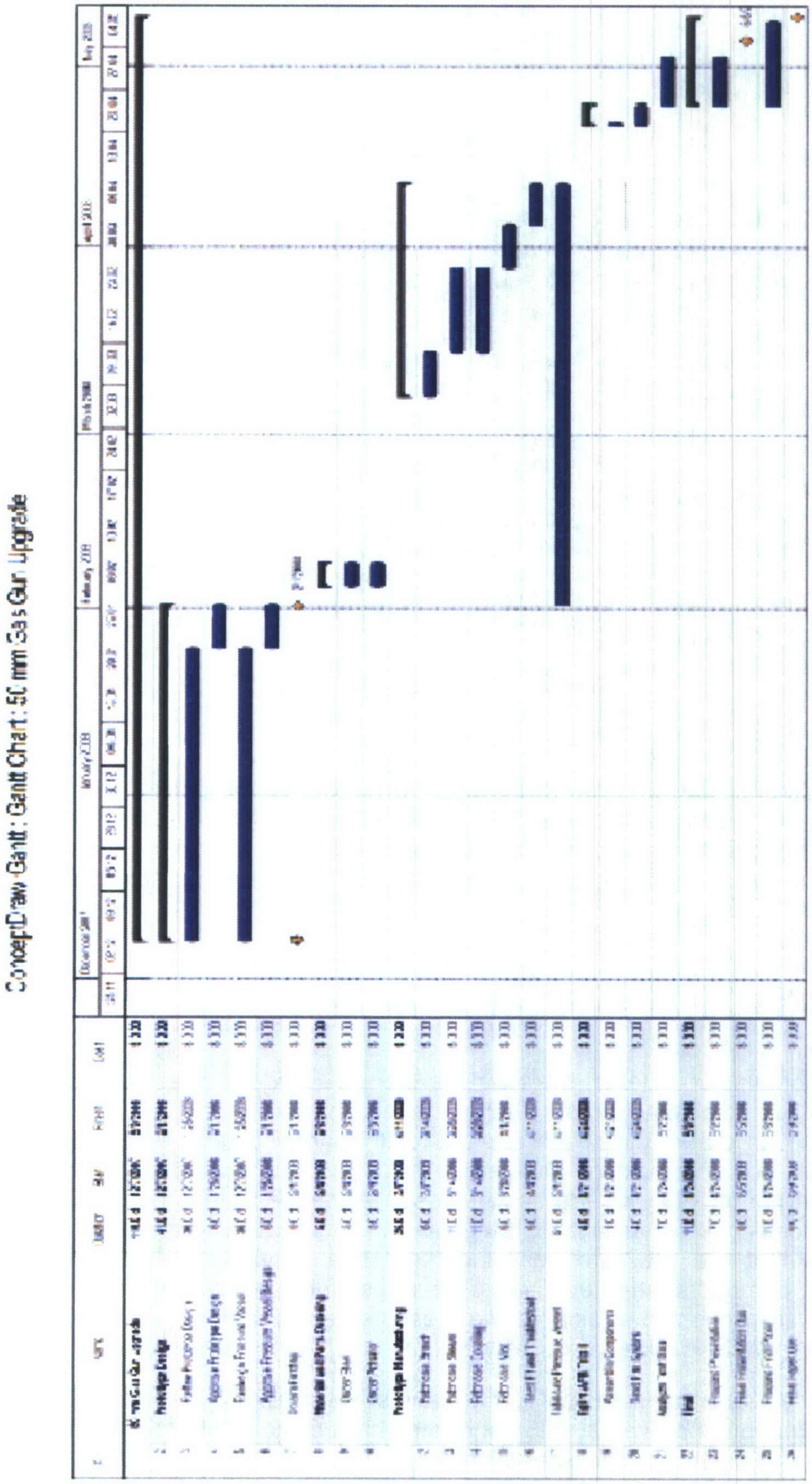

Figure 25: Schedule

Testing

Before traveling to the base to fire the gun, a test plan was made to determine the shots to be fired. The team decided that ten shots would not be enough to produce an accurate curve to predict velocity. Instead of trying to make a curve, the test plan was setup to prove reliability. The matrix seen in the table has five air shots and five helium shots.

Day	Gas	Pressure	Mass	Predicted Velocity (ft/s)
Wednesday	Air	350 psi	700 grams	490
Wednesday	Air	1750 psi	350 grams	1290
Wednesday	Air	1750 psi	350 grams	1290
Thursday	Air	3000 psi	350 grams	1642
Thursday	Air	3000 psi	350 grams	1642
Thursday	Helium	3000 psi	350 grams	1680
Thursday	Helium	3000 psi	350 grams	1680
Friday	Helium	2500 psi	350 grams	1545
Friday	Helium	2000 psi	700 grams	1390
Friday	Helium	2000 psi	700 grams	1390

Figure 26¨ Planned test matrix

The first shot with air was to determine whether or not the gun would fire successfully. The next four test repeatability at two different pressures. With helium the same concept is used to test repeatability. If these shots would have been successful than further testing could have been done to create a curve to find need pressure for a given mass and desired velocity.

Results and Analysis

After fabrication was completed, the team traveled to Florida to assemble and test fire the gun. A few problems arose during the assembly of the gun. First, due to miscommunication the length of the threads for the larger couple was too long. The couple was taken to the machine shop at the base and cut down to proper size. Next, the sleeve did not fit tightly on the barrel. A spacer needed to be inserted in order to simplify the loading process and to stop unwanted vibrations after firing. Another problem was that the pressure vessel did not seal properly. This was fixed by bypassing the pump to shorten the filling time and shooting at lower pressures. The air supply tank was connected straight to the pressure vessel, and the valve was opened completely. When the desired pressure was reached the gun was fired.

After the assembly was completed, four shots were taken. The first two were successful. The first shot was at 338 psi of air with a payload of 1110.6 grams. The expected velocity for this pressure and mass was around 450 ft/s. The projectile was fired at 360 ft/s. The second shot was at 910 psi of air with a payload of 762 grams and an expected velocity of 940 ft/s. This projectile was fired at 1008 ft/s. Due to time constraints the test plan was altered for the next shot. This shot was taken at 231 psi of air with a mass of 761 g. This shot was taken at the same pressure/mass ratio as shot #1 to determine if the gun fires consistently. The velocity should have been the same as the first shot but this attempt failed. The projectile came out of the barrel but the obturator became wedged a third of the way down the barrel. The fourth shot, which used helium, also was unsuccessful. It was taken at 1189 psi and a payload of 763.2 grams. Again the projectile came out of the barrel but the obturator was wedged in the middle of the barrel. The failure of these two shots was due to a few reasons. First, the sleeve slightly shifted back after the second shot and the team did not notice. The balls did not completely release, which caused the obturator to release slowly and possible blow by to occur. Also, once the projectile is released gas is allowed to escape through the four holes in the breech. For the low pressure shot, any volume lost is critical and needed force is lost. For the helium shot, the helium leaked extremely quickly through the holes to lose pressure. The helium also may have leaked past the projectile, because the pressure vessel was leaking and it was not known if the projectile sealed properly. The final problem deals with the plastic filler that was inserted into the pressure vessel. When the gun is fired a pressure differential is created and the plastic filler is pushed to the front of the pressure vessel. The filler could have possibly moved all the way forward and restricted the gas from coming out of the pressure vessel

Improvements

Improvements can be made in order to produce more successful shots. First, the sleeve needs to be sealed to prevent gas from leaking out of the breech after the projectile is released. This will be done by inserting a metal spacer, which will also help to steady the sleeve, on one side of the sleeve. On the other side of the sleeve an o-ring will inserted to prevent leaks. Next, a stop will be welded to the breech to ensure that the sleeve is positioned correctly. Also, the pieces of the sabot will be decreased in diameter by ten thousandths, because the two shots that went through the barrel were slightly extruded. Finally the plastic filler needs to be secured to the back of vessel or moved back after each shot. With these improvements, the gun should be able fire better and more consistent. Another improvement that allows for a quicker turn around time is to add handles to the breech/vessel couple. This will allow the couple to be quickly and easily tightened to the breech and vessel.

Summary

The quick release design was a great improvement from the other designs, but it incorporates some previous design ideas such as allowing for an instantaneous release of the projectile and the driving gas by using the obturator on the back of the projectile while using some mechanical device to hold the projectile in place. This set up allows the gas to flow through the barrel without being choked through a small valve. The overall set up took some time but the turn-around time between shots was as expected. Although all of the design objectives were not met due to time constraints, the concepts of the design were shown to be feasible by the experimentation, and the team did meet the objectives of turnaround time, not using explosives, and making the system interchangeable with the current breech. The two successful shots followed the empirical data and show that the design has a good chance of being effective with the suggested improvements of adding a stopper to the breech, an o-ring to the sleeve, and sealing the pressure vessel adequately.

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